View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Elsevier - Publisher Connector

Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 72 (2015) 42 – 48
Energy Procedia

International Scientific Conference "Environmental and Climate Technologies – CONECT 2014"

Experimental study on the effects of air velocity, temperature and depth on low-temperature bed drying of forest biomass residue

Krista Klavina*, Armands Cinis, Aivars Zandeckis

Riga Technical University, Institute of Energy Systems and Environment, Azenes iela 12/1, Riga, LV 1048, Latvia

Abstract

Experiments are carried out for a wood chip bed dryer with a perforated floor. Methodology for the calculation of a benefit-cost ratio is created and validated with experimental results. Statistical analysis was performed and empirical models with non-linear multivariate correlation equations describing the drying rate, and the benefit-cost ratio were developed. With the appropriate adjustments this methodology can be used for the economic evaluation of a biomass dryer.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of Riga Technical University, Institute of Energy Systems and Environment

Keywords: Wood chips, Drying, Low temperature, Biofuel, Bed dryer, Box-Behnken design

1. Introduction

The European Commission has set new targets to reach a low-carbon economy. Among the key elements is the renewable energy target of at least 27 % renewable energy resources (RES) in energy consumption in 2030 [1] continuing to raise the 2020 bar of 20 % RES [2]. The target recommended by the European Renewable Energy Council is 45 % [3]. In 2011 in the EU-27 a share of 13.0 % of gross final energy consumption was from renewable energy [2], and the most important renewable energy source continues to be biomass with 64 % from the gross inland consumption of RES [4]. Effort has to be made to reach these targets, but simultaneously sustainable, efficient use of biomass has to be assured.

* Corresponding author. Tel.: +371-6708-9943; fax: +371-6708-9908
E-mail address: krista.klavina@rtu.lv

1876-6102 © 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of Riga Technical University, Institute of Energy Systems and Environment
doi:10.1016/j.egypro.2015.06.007

Biomass drying is significant for several reasons depending on application. In the combustion processes, drying is required to increase the net calorific value of biomass and to improve combustion process efficiency, as a result the dimensions of the boiler can be reduced, the unburned solid particulate matter emissions [5] and the consumption of primary energy decreased. When storage of biomass is necessary, drying can be used as a tool to reduce the loss of dry matter due to microbial activity [6, 7] that leads to energy loss and greenhouse gas emissions [8]. Biomass drying to match the requirements of the production specifications is required in pellet production, the feedstock has to be dried to around 10 % moisture content [9, 10], and likewise for briquetting [11]. The synfuel production process requires 10–15% moisture content [12, 13].

Nomenclature

β_0	Constant coefficient
β_1, β_2, β_3	Linear regression coefficients
β_{11}, β_{22}, β_{33}	Quadratic regression coefficients
β_{12}, β_{13}, β_{23}	Interaction effects of the model
E_f	Benefit of fuel drying, €
E_p	Cost of parasitic energy consumption, €
H	Dried layer thickness, m
h_a	Enthalpy of the ambient air at the initial temperature and relative humidity, kJ/kg
h_i	Enthalpy of the inlet air at the inlet temperature and relative humidity conditions, kJ/kg
m_2, m_1	Mass of dried and fresh biomass respectively, kg
m_a	Mass of heated air during drying period, kg
η	Efficiency of heat energy production
$\eta_{a.h}$	Efficiency of air heater
$Q_{f.p.}$	Fan electricity consumption, kWh
Q_{z2}^d, Q_{z1}^d	Net calorific value of dried and fresh biomass respectively, MJ/kg
S_i	Area at the measurement point, m^2
t	Time, s
T	Temperature, °C
T_{el}	Electrical energy price, €/kWh
T_h	Heat energy price, €/MWh
υ	Air flow velocity, m/s
W	Drying rate, %/h
Y	Predicted response
ρ	Density of air, kg/m^3

Low-temperature drying has significant benefits over high temperature drying. The low temperature settings allow the use of low-potential heat that can be attained as a waste product from different manufacturing processes or supplied using renewable resources. The low temperature settings also reduce the own use of biomass in the dryers. For example in Sweden 12 % of the entering timber is consumed in the production process [14]. Lower temperature settings also have smaller heat loss through the dryer envelope. Apart from these positive economic and environmental effects, the use of low temperature drying reduces direct emissions to air. Drying of bark chips with superheated steam produces organic compounds in the exhaust steam [14]. High temperature drying of freshly cut spruce and birch indicate fumes containing volatile mutagenic compounds [15]. The organic compounds emitted during the drying with hot air or steam, are identified mainly as monoterpene and sesquiterpene hydrocarbons [16]. The amount of emitted organic compounds can be minimized with drying in lower temperatures [14, 16]. In addition, drying process type has an effect on energy consumption during pelletisation – high temperatures for drying of the raw material lead to greater energy consumption during pelletisation [9].

This paper deals with drying of wood chips in a packed bed vertical dryer with a perforated floor and a bottom air supply. Most often these biomass dryer designs are “experience based”, and there are few scientific studies dealing with the kinetics of the biofuel drying process [17]. Pringle and Pan [18] have carried out an experiment of wood chip deep bin drying with fungal measurements for the evaluation of a drying model. Ozollapins et al. [19] have studied the drying rate of reed canary grass, reed and hemp stalks, and peat with varying drying bin layer thickness. Lerman and Wennberg [20] have carried out an experimental study on the drying of sawdust and wood chips in a bed dryer with a focus on the movement of drying zones.

2. Material and methods

2.1. Design of the experiment

Three variable factors are selected – height of the wood chip layer (0.5 – 1.0 – 1.5 m), air velocity (0.03 – 0.13 – 0.22 m/s) and temperature (20.0 – 28.5 – 37.0 °C). The response variable measured is the weight of the dried product (kg) which is used for calculation of the drying rate. A multivariate optimization with a single response surface is selected within this study. The Box-Behnken design is selected as a fractional factorial design. The number of experiments (*N*) in Box-Behnken design can be expressed as $2k\cdot(k - 1) + Co$, where k is the number of factors and *Co* the number of replicate central points [21]. Thus in this experimental study, the total number of fifteen experimental runs are required, $N = 2\cdot3\cdot(3 - 1) + 3 = 15$. A quadratic regression model as displayed in (1) [22, 23] is applied to the gathered experimental results.

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 \quad (1)$$

The STATGRAPHICS Centurion 16.1.15 tool is used for the development of the experimental model and the data analysis.

2.2. Material – wood chip characterization

The biomass used in this drying experiment is a fine wood chip material with the median particle size distribution at 15.9 mm according to LVS EN 15149-1:2011 [24]. The same material is used in all experimental runs, the wood chips are rewetted by submerging in water, draining and then storing in a sealed container for at least 24 hours to equalize the moisture content in the whole wood chip body.

2.3. Experimental setup

An experimental rectangular vertical batch bed dryer with a perforated floor and a maximum loading capacity of 0.65 m^3 is used for the wood chip drying. The experimental dryer has a bottom-up air supply with an electrical fan. The setup is similar to that used in the study by Lerman and Wennberg [20]. A schematic representation of the experimental set-up, and the used equipment and its placement in the experimental drying bin is visible in Fig.1. In the experimental runs with an increased air temperature, an air heater is placed at the air inlet, and also the whole room temperature is raised.

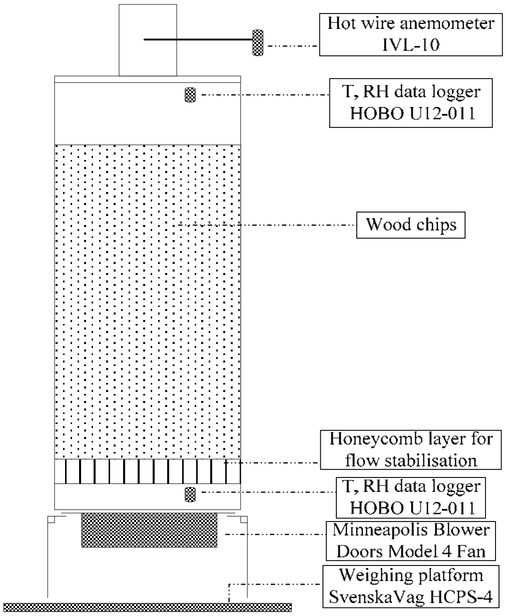

Fig.1. Experimental set-up schematic representation

2.4. Drying experiment procedure

First a sample of the wet wood chips is taken. The initial moisture content of wood chip samples is determined according to LVS EN 14774-2:2010 [25]. The material is loaded into the experimental dryer bin manually from the top, the material falls naturally, and no additional compaction is applied. Each drying experiment is run for 24 hours. The final moisture content is calculated from the weight change recorded by the weighing platform beneath the experimental dryer.

3. Results and discussion

3.1. A. Drying rate evaluation

The discussed results are valid in the limits of the parameter values selected in the experimental evaluation. Applying them to a different parameter range can lead to false conclusions. First, the relation of the wood chip drying rate is analyzed in regards to the set parameter values. The R-Squared statistic indicates that the model as fitted explains 97.8 % of the variability of the drying rate, the R-Squared (adjusted for degrees of freedom), that is more suitable for the comparison of models with a different number of independent variables, is 93.9 %. The Standard Error of Estimate that represents the standard deviation of the residuals is 0.133. The average value of the residuals or the mean absolute error is 0.0641. Durbin-Watson (DW) statistic tests the residuals to determine if there is any significant correlation based on the order in which they occur in the data file. Since the P-value is greater than 5.0 %, that is 0.872, there is no indication of serial autocorrelation in the residuals at the 5.0 % significance level. The drying rate is separated into separate pieces for each of the effects in the ANOVA table. The statistical significance of each effect is tested by a comparison of the mean square against an estimate of the experimental error. In this study 5 effects have P-values less than 0.05, indicating that they are significantly different from zero at the 95.0 % confidence level.

It is possible to optimize the drying rate of solid biomass by varying the temperature, air velocity and the thickness of the drying material layer. An important parameter that can be applied for the process optimization – drying agent saturation – is not discussed within this study [26]. The standardized Pareto Chart in Fig.2 indicates the effects with the greatest impact on the drying rate. The standardization is made by dividing the value of each variable by its standard error.

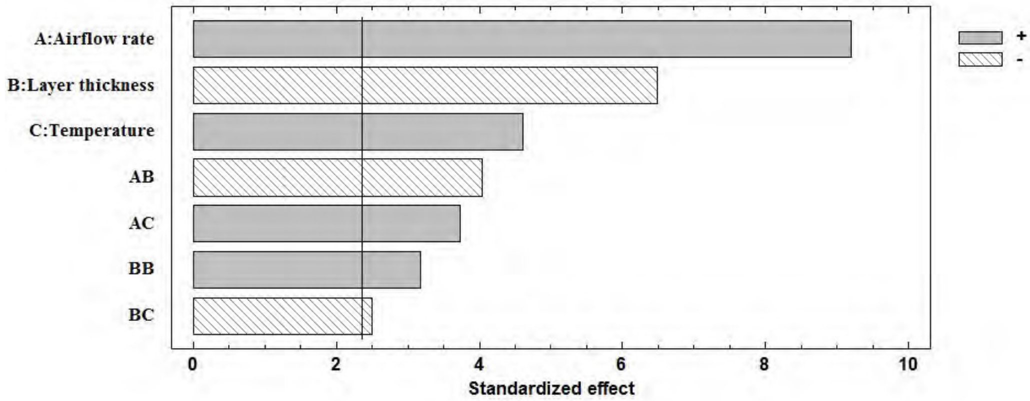

Fig.2. Standardized Pareto Chart for drying rate

The highest detected positive impact is related to the airflow speed while the highest negative impact belongs to the thickness of the wood chip layer. Temperature has a smaller effect on the drying rate than the airflow rate and layer thickness. The vertical line in the graph in Fig.2 represents the statistically significant variables at the 5 % significance level. As the interactions AA, CC are below the significance level, they are excluded from the mathematical model.

The regression analysis is carried out with the statistically significant variables and the empirical regression equation for the drying rate is obtained as visible in (2).

$$W = -6.08284 - 0.9998 \cdot \upsilon + 0.1428 \cdot H + 0.04711 \cdot T - 5.5972 \cdot \upsilon \cdot H + 0.4792 \cdot \upsilon \cdot T + 0.7891 \cdot H^2 - 0.06521 \cdot H \cdot T \quad (2)$$

In the current model, the airflow rate and temperature has a linear effect on the drying rate and a non-linear interaction is noticed between the layer thickness and the drying rate value. The empirical equation (2) is plotted in a 3-dimentional surface for the case with 30.0 °C temperature in Fig.3. It is clearly visible that with decreasing wood chip layer and an increasing air flow, the drying rate is enhanced. In the current model the drying rate-air flow relation is more intense than the drying rate-layer thickness relation.

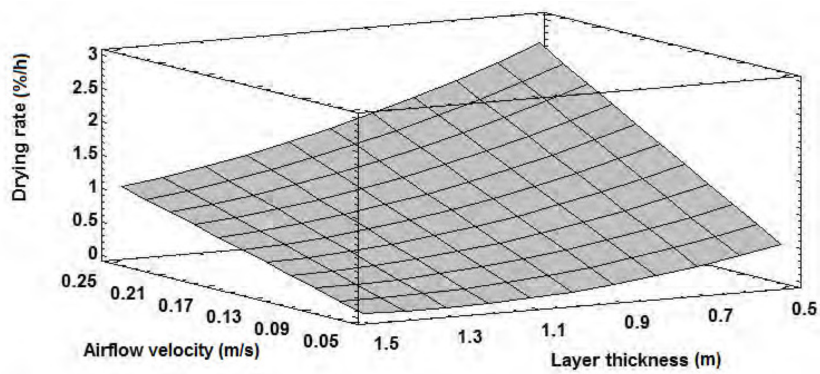

Fig.3. Estimated Response Surface at 30 °C

3.2. Benefit-cost ratio

The selected temperature, airflow velocity, and layer thickness is closely related to the economic feasibility of the dryer. An optimum has to be selected between the best drying conditions and the lowest operational costs.

In order to characterize the dryer operational parameters in economic terms, a methodology is developed to calculate the benefit-cost ratio (E_f/E_p). This is the proportionality relation of the increased energy extraction due to the increased net calorific value of the dried material, and the energy consumption for the fan powering and the air heating. These parameters are expressed in monetary values.

The parameter E_f is the benefit from fuel drying; it can be calculated according the equation (3).

$$E_f = \left(m_2 \cdot Q_{z_2}^d - m_1 \cdot Q_{z_1}^d\right) \cdot \eta \cdot T_h \cdot \frac{1}{3600} \tag{3}$$

The benefits of fuel drying are contrasted to the parasitic energy consumption E_p. this parameter is calculated according to the equation (4).

$$E_p = Q_{f.p.} \cdot T_{el} + \frac{(h_i - h_a) \cdot m_a \cdot T_h}{\eta_{a.h.} \cdot 3.6 \cdot 10^6} \tag{4}$$

The parameters used in equation (4) are representing the influence of the dryer operational parameters on the expenses of the drying process. The fan electricity consumption is directly associated to dryer air flow velocity, and dried material layer thickness. The enthalpy values used in eq. (4) can be found in handbooks of psychrometrics in the thermodynamic tables for moist air at each temperature and relative humidity conditions. The mass of the heated air is obtained according to equation (5).

$$m_a = \rho \cdot v \cdot S_i \cdot t \tag{5}$$

Ratio E_f/E_p should be maximized by reducing the consumed energy costs, using cheaper energy sources, lowering the drying temperature or reducing the air flow rate. Drying temperature and air flow velocity have to be selected by optimisation because it simultaneously affects the increase of the dried material net calorific value. The developed methodology is validated with experimental results. Statistical analysis is performed using STATGRAPHICS. The quadratic regression model (1) is fitted to the results, and it explains 66.5193 % of the variability in the E_f/E_p ratio. The greatest negative effect on the E_f/E_p has the mass flow rate, in experimental parameter range the temperature and layer thickness has a positive impact on E_f/E_p ratio, because the increased energy gain covers the energy spending. The benefit-cost ratio relation to the air mass flow rate, temperature and the dried wood chip layer thickness is also expressed in a regression equation (6).

$$E_f/E_p = 0.08829 + 0.04636 \cdot H - 0.00006225 \cdot \dot{m} + 0.002266 \cdot T + 0.09234 \cdot H^2 - 0.000007428 \cdot H \cdot \dot{m} - 0.00523 \cdot H \cdot T + 2.09954 \cdot 10^{-9} \cdot \dot{m}^2 + 0.000001504 \cdot \dot{m} \cdot T \tag{6}$$

The R-squared value is quite small due to the small number of experiments for this complex problem solving, thus the equation cannot be used for precise calculations.

4. Conclusions

In the scope of this work, the methodology for the calculation of benefit-cost ratio was developed for the characterization of the dryer performance. The methodology was verified using the experimental results. This methodology with the appropriate adjustments can be used for economic evaluation of biomass drying technologies. Statistical analysis was performed using the STATGRAPHICS Centurion 16.1.15 statistical data analysis tool, and the empirical models with non-linear multivariate correlation equations describing the drying rate, and the benefit-cost ratio in function of the drying temperature, air flow velocity, and wood chip layer thickness were created.

During experimental data statistical analysis, the independent variable weight analysis was performed, distinguishing the variables with strongest influence on the developed empirical models. In the presented experimental range it is discovered that the dryer air flow rate has the strongest positive influence on the drying rate and the strongest negative influence on the benefit-cost ratio.

Acknowledgements

The work has been supported by the National Research Program “Energy efficient and low-carbon solutions for a secure, sustainable and climate variability reducing energy supply (LATENERGI)”.

References

[1] European Commission. 2030 climate and energy goals for a competitive, secure and low-carbon EU economy 2014. [Online]. Available: http://europa.eu/rapid/press-release_IP-14-54_en.htm.
[2] European Commission. Headline indicators 2014. [Online]. Available: http://epp.eurostat.ec.europa.eu/portal/page/portal/europe_2020_indicators/headline_indicators.
[3] J. Muth and E. Smith. 45% by 2030 Towards a truly sustainable energy system in th EU 2011.
[4] European Commission. Energy from renewable sources 2013. [Online]. Available: http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Energy_from_renewable_sources.
[5] H. Li, Q. Chen, X. Zhang, K. N. Finney, V. N. Sharifi, and J. Swithenbank. Evaluation of a biomass drying process using waste heat from process industries: A case study. *Appl. Therm. Eng*. 2012; 35: 71–80.
[6] M. Pettersson and T. Nordfjell. Fuel quality changes during seasonal storage of compacted logging residues and young trees. *Biomass and Bioenergy* 2007; 31(11–12): 782–792.
[7] J. Nurmi and K. Hillebrand. The characteristics of whole-tree fuel stocks from silvicultural cleanings and thinnings. *Biomass and Bioenergy* 2007; 31(6): 381–392.
[8] E. Jäppinen, O.-J. Korpinen, J. Laitila, and T. Ranta. Greenhouse gas emissions of forest bioenergy supply and utilization in Finland. *Renew. Sustain. Energy Rev*. 2014; 29: 369–382.
[9] T. Filbakk, G. Skjevrak, O. Høibø, J. Dibdiakova, and R. Jirjis. The influence of storage and drying methods for Scots pine raw material on mechanical pellet properties and production parameters. *Fuel Process. Technol*.2011; 92(5): 871–878.
[10] M. Ståhl, K. Granström, J. Berghel, and R. Renström. Industrial processes for biomass drying and their effects on the quality properties of wood pellets. *Biomass and Bioenergy* 2004; 27(6): 621–628.
[11] H. Yumak, T. Ucar, and N. Seyidbekiroglu. Briquetting soda weed (Salsola tragus) to be used as a rural fuel source. *Biomass and Bioenergy*, 2010; 34(5): 630–636.
[12] L. Fagernäs, J. Brammer, C. Wilén, M. Lauer, and F. Verhoeff. Drying of biomass for second generation synfuel production. *Biomass and Bioenergy* 2010; 34(9): 1267–1277.
[13] J. Isaksson, A. Åsblad, and T. Berntsson. Influence of dryer type on the performance of a biomass gasification combined cycle co-located with an integrated pulp and paper mill. *Biomass and Bioenergy* 2013; 59: 336–347.
[14] H. Bjork and R. Anders. Formation of organic compounds in superheated steam drying of bark chips. *Fuel Energy Abstr*. 1996; 37(2): 115.
[15] P. Kurttio, P. Kalliokoski, S. Lampelo, and M. J. Jantunen. Mutagenic compounds in wood-chip drying fumes. *Mutat. Res.,* 1990; 242(1): 9–15.
[16] K. Rupar and M. Sanati. The release of organic compounds during biomass drying depends upon the feedstock and/or altering drying heating medium. *Biomass and Bioenergy* 2003; 25(6): 615–622.
[17] R. Wimmerstedt. *Drying of Peat and Biofuels. Handbook of Industrial Drying*. 3rd ed., A. S. Mujumdar, Ed. Boca Raton: Taylor & Francis; 2006: 743–752.
[18] R. T. Pringle and J. N. Pan. *Storage and Drying of Comminuted wood fuel*. Proceedings from Joint-meeting IEA/BEA Activity 4 and 5, 1991:165–178.
[19] M. Ozollapins, A. Kakitis, and I. Nulle. Stalk biomass drying rate evaluation. 2013: 482–487.
[20] P. Lerman and O. Wennberg. Experimental method for designing a biomass bed dryer. *Biomass and Bioenergy* 2011; 35: S31–S39.
[21] S. L. C. Ferreira, R. E. Bruns, H. S. Ferreira, G. D. Matos, J. M. David, G. C. Brandão, E. G. P. da Silva, L. a Portugal, P. S. dos Reis, a S. Souza, and W. N. L. dos Santos. Box-Behnken design: an alternative for the optimization of analytical methods. *Anal. Chim. Acta.* 2007; 597(2): 179–86.
[22] Montgomery and C. Douglas, Design and Analysis of Experiments Eights Edition International Student Version. Arizona: John Wilwy & Sons, Inc., 2013.
[23] R. Lahlali, S. Massart, M. N. Serrhini, and M. H. Jijakli. A Box-Behnken design for predicting the combined effects of relative humidity and temperature on antagonistic yeast population density at the surface of apples. *Int. J. Food Microbiol*. 2008; 122(1−2): 100–8.
[24] LVS, Solid biofuels - Determination of particle size distribution - Part 1: Oscillating screen method using sieve apertures of 1 mm and above. 2011; 2010.
[25] LVS, Solid biofuels - Determination of moisture content - Oven dry method - Part 2: Total moisture - Simplified method. 2010.
[26] J. Selivanovs, D. Blumberga, J. Ziemele, A. Blumberga, A. Barisa. Research of Woody Biomass Drying Process in Pellet Production. *Environmental and Climate Technologies* 2013; 10: 46-50.